RECENT TECHNOLOGY DEVELOPMENTS FOR THE KINETIC KILL VEHICLE HARDWARE-IN-THE-LOOP SIMULATOR (KHILS)

Robert Lee Murrer, Jr.*
Rhoe A. Thompson
Charles F. Coker

Air Force Research Laboratory
Munitions Directorate, Eglin AFB FL

Abstract:

The Ballistic Missile Defense Organization (BMDO) developed the Kinetic Kill Vehicle Hardware-in-the-Loop Simulator (KHILS) to provide a comprehensive ground test capability for end game testing of BMDO interceptor concepts. Since its inception in 1986, the KHILS facility has been on the forefront of HWIL test technology development. This development has culminated in closed-loop testing involving large format resistive element projection arrays, 3-D scene rendering systems, and real-time high fidelity phenomenology codes. Each of these components has been integrated into a real-time environment that allows KHILS to perform dynamic closed-loop testing of BMDO interceptor systems or subsystems. This paper describes the development status and test results of the major facility components.

I. Introduction

The cost and complexity of BMDO's Infrared (IR) guided interceptor systems require reducing the number of flight tests needed for critical program decisions to a fraction of those traditionally flown for conventional munition programs. Instead, BMDO programs must rely on an exhaustive series of ground tests to better understand and characterize the weapon system. These ground tests include, at a minimum, sub-component characterization and Hardware-in-the-Loop (HWIL) testing and may include integrated propulsion system evaluation during hover testing[1]. HWIL provides a synthetic environment where a weapon system, or its components, can be evaluated in a nondestructive manner under known and controlled conditions. Successful HWIL testing involves reaching the correct level of compromise between the "real-world" and the synthetic environment offered by the HWIL facility so that the HWIL facility has no detrimental effects on estimates of system performance.

HWIL testing can have several forms but is normally associated with real-time closed-loop testing of the seeker, gimbal, signal processor, guidance processor, and inertial measurement unit. Vehicle control systems that rely on chemical thrusters are included as digital models only. HWIL testing can be used early on in a program using laboratory brassboard components that are functionally equivalent to intended flight hardware and digital simulations of other components that may not be available. One of the chief challenges to the HWIL facility is to provide adequate physical stimuli to the seeker and inertial measurement instrumentation while providing the proper modeling of the engagement kinematics of both the weapon and target.

Many aspects of Kinetic Kill Vehicles (KKV) being developed for the BMDO depart in concept and design from traditional tactical weapons and therefore impact the requirements of the HWIL facility destined to test the system. For example, KKVs have a high degree of autonomy, a widely varying target set, extreme environmental

* Further author information:
R.L.M.: (850) 882-4446, x 2271, murrer@eglin.af.mil
R.A.T.: (850) 882-4446, x 2273, thompsra@eglin.af.mil
C.F.C.: (850) 882-4446, x 2264, cokerc@eglin.af.mil

conditions, and no warhead. KKVs perform a lengthy fly out that places the vehicle in a small "kinematic window" from which it must intercept the target. Handover from the inertial fly-out phase to the onboard imaging infrared seeker comes from an off-board sensor that derives target-position information and passes its best estimate to the interceptor. The interceptor must correlate between the objects seen by off-board sensors and those it sees when it opens its eyes. To test this critical function, the HWIL facility must ensure it provides the correct spatial, temporal, radiometric, and spectral characteristics of the target(s) and debris. Given the kinematic limitations of the interceptor, choosing the wrong object in such a critical phase of the engagement could be disastrous even if the correct target is later correctly identified. Therefore, the sensor's ability to detect, identify, and track the target must be included as a part of HWIL testing.

Once the target is identified, the track phase begins where the interceptor "concentrates" only on the target. The challenges associated with this phase of the intercept involve the interaction between the interceptor and its environment. The ability of the vehicle to accommodate environmental factors that may affect its performance such as window heating, body coupling, and jet interaction must be accounted for by the models of the HWIL facility. During the terminal phase of the engagement, a correct aimpoint selection must be made in the presence of the above environmental factors and an extremely fast growing target. The HWIL facility must be able to correctly simulate the dynamics of target growth and its spatial representation to confidently assess the interceptor's ability to lethally impact the target.

An aggressive development effort was instituted by the HWIL test community to meet the challenges raised by BMDO's emerging class of KKVs. This paper describes the successes of the KHILS facility to meet these challenges through the development and fielding of efficient accurate target phenomenology models, real-time image rendering systems, and high fidelity IR scene projectors. KHILS has integrated each of these components into a common test environment that provides the BMDO with a flexible, robust, and completely unique test resource for the accomplishment of flight test risk reduction and guided interceptor development.

II. Background

In 1986 the Strategic Defense Initiative Organization (SDIO) began funding the development of a dedicated HWIL test capability at Eglin Air Force Base to support the emerging class of highly complex imaging IR KKV

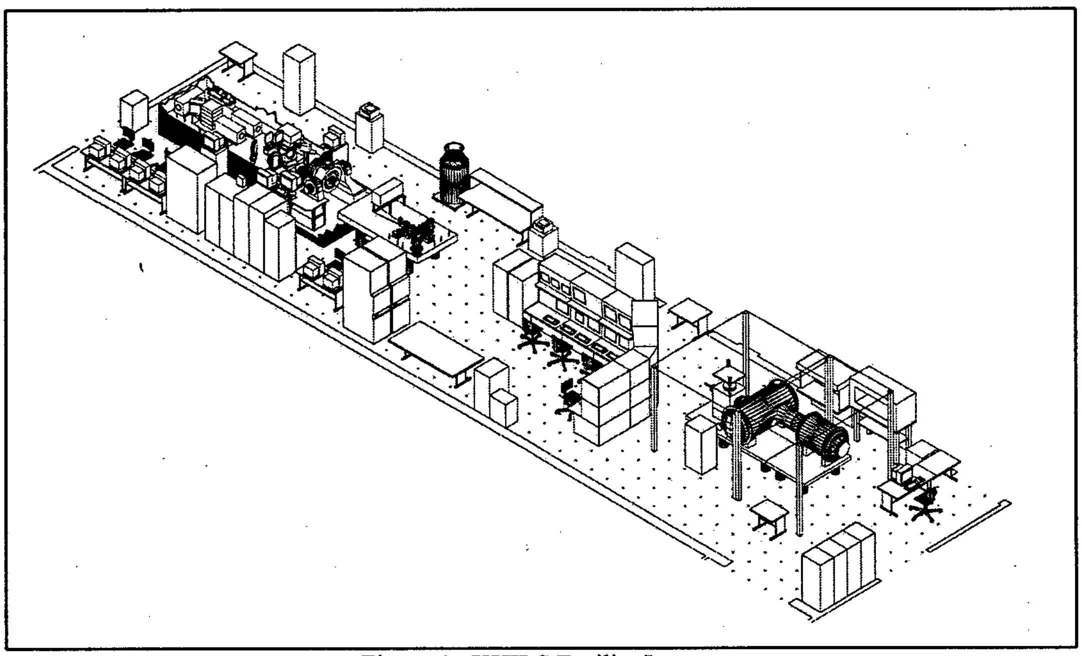

Figure 1. KHILS Facility Layout

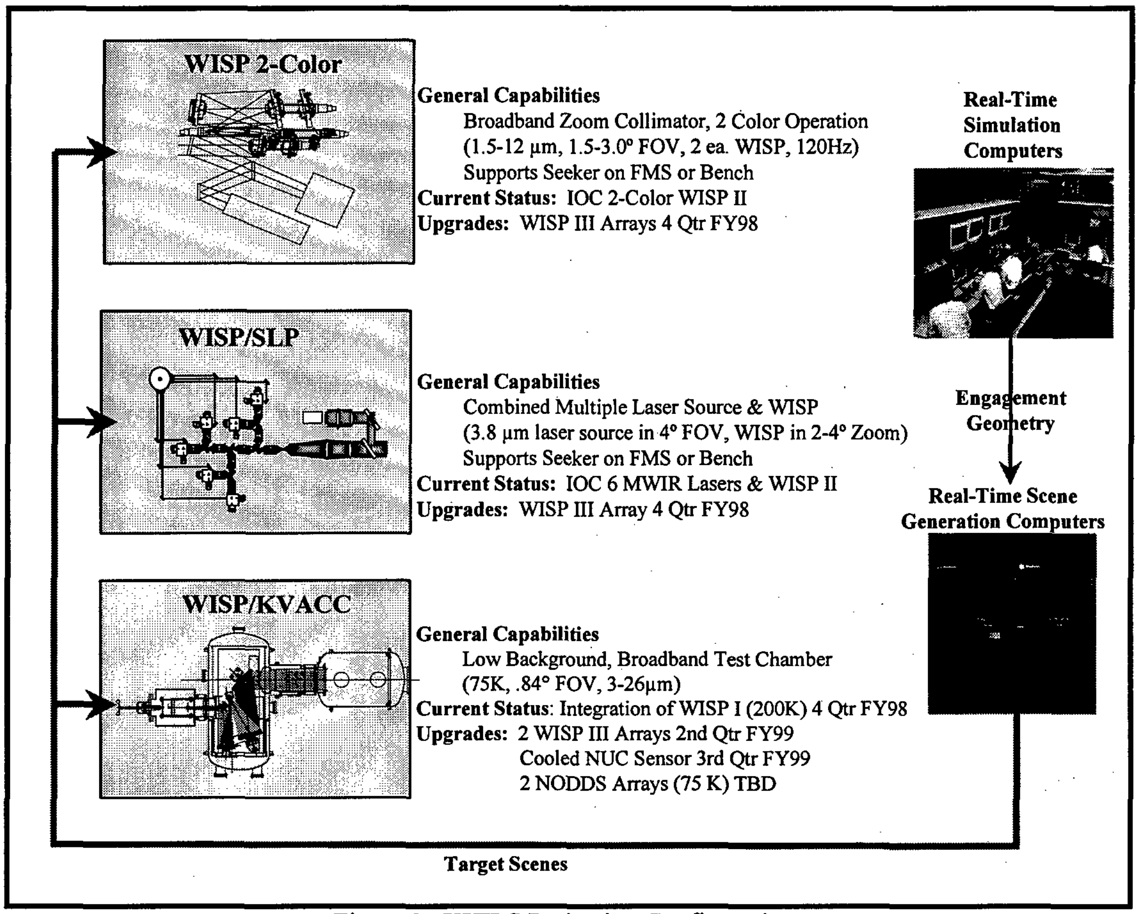

Figure 2. KHILS Projection Configurations

systems. Faced with developing separate facilities to address specific program needs, the SDIO elected to establish a HWIL capability at a single site where a common experience base could be established that would benefit all programs regardless of development phase. Many capable HWIL facilities existed at the time with the potential to fill this role. The Air Force Armament Laboratory (AFATL)[†], having established several Air Force interceptor and HWIL technology base programs and recently completing development of the Advanced Medium Range Air-to-Air Missile (AMRAAM) HWIL facility, was chosen as the site for the Kinetic Kill Vehicle Hardware-in-the-Loop Simulator (KHILS). The AMRAAM HWIL development experience was significant in that AMRAAM represented the first of a new generation of all-weather launch-and-leave tactical weapons. Having complete re-programmability, a large target set, and electronic countermeasure capability, the AMRAAM required comprehensive high fidelity HWIL ground testing prior to flight. The same team that designed, built, and configured the AMRAAM facility was called upon to lay the groundwork for the KHILS facility. Parallel to the AMRAAM facility development, an advanced instrumentation group within AFATL was spearheading several HWIL technology base efforts. These efforts focused on two areas: real-time 3-D scene generation and dynamic infrared projection. By leveraging off both the AMRAAM facility design and the HWIL technology base efforts, KHILS demonstrated initial operational capability (IOC) in 1988.

Today, KHILS[2] occupies a 22' x 110' high bay complex and various technician and analyst work areas adjacent to the now retired AMRAAM facility. Shown in Figure 1, the main bay of the KHILS facility houses the computational

[†] AFATL is now the Munitions Directorate of the Air Force Research Laboratory (AFRL/MN)

resources, physical effects simulators, and chamber systems necessary to accomplish HWIL testing of a wide variety of interceptor systems. Currently, KHILS has the real-time computers, scene generation, and IR projection resources to conduct three simultaneous HWIL tests with minimal conflict. Depicted in Figure 2, this capability uses one of several projection and optical systems developed for KHILS. The "WISP 2-Color" utilizes two co-aligned resistor arrays in an all-reflective broadband zoom optical collimator. The "WISP/SLP" system uses the same resistor array technology but combines it with a multi-source laser projector system. Both systems will support sensors mounted on either an optical bench or a flight motion simulator. The "KVACC" system is being brought on line currently and is designed to incorporate one or two resistor arrays for HWIL testing of seekers requiring background temperatures below laboratory ambient conditions. The inherent flexibility built into each of these systems allows variations in optical systems, listed in Table 1, to be readily accommodated. Figure 3 shows the various modes in which the scene generation, projection, and flight motion devices can be configured to accommodate a unit under test. KHILS has published extensively on its test technology development activities. Many of these papers are cited as references throughout this paper and can be obtained through the SPIE conference proceedings. Other references may be obtained through the Defense Technical Information Center (DTIC) or directly from the authors.

TYPE/Zoom	Wavelength (micron)	EFL (inches)	Pupil Dia. (cm)	[illegible]
Refractive/5:1	3-5	4-18	7.62	3.26-14.67
Refractive/2:1	3-5	28.8-14.4	14	2.0-4.0
Refractive/35%	3-12	16.34-12.09	6	3.52-4.77
Refractive Singlet/none	4-11	11.9	5.5	4.8
Refractive Singlet/none	4-11	9.15	5	6.3
Refractive/none	3-5	3.5	N/A	16.67
Reflective/2:1	1.5-12	39.2-19.6	15	1.5-3.0
Reflective/none	3-26	70	30	.84
Off-Axis-Parabola/none	Broadband	50	15	1.15
Off-Axis-Parabola/none	Broadband	40	15	1.44

Table 1. KHILS Optical Collimators

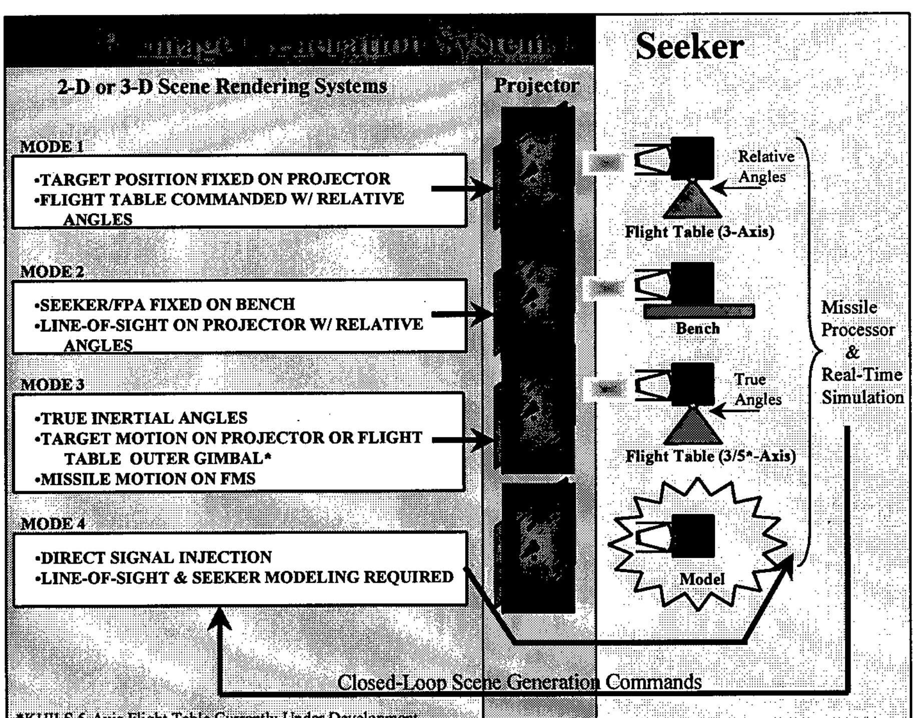

Figure 3. KHILS Modes of Operation

III. Test Technology Development

KHILS test technology development has three primary thrusts: 1) Target/Background Signature Modeling, 2) Real-Time Scene Generation, and 3) Infrared Scene Projection. In each case, the goals are to maximize fidelity and maintain flexibility. Given KHILS's role as an independent assessor and the technical and political scrutiny associated with this function, achieving the highest fidelity is paramount. Each of the sections below gives a brief description of the development approach and overview of the major simulator components. Further described are the environmental chambers, flight motion simulator, and advanced development efforts necessary for KHILS to support its BMDO customer.

A. Phenomenology Models.

The IR scene generation process begins with the creation of databases that model the target, background, countermeasures, and environmental effects. Figure 4 shows the flow process and modeling codes used to build up these databases. Once the target geometry is defined, an analysis of the engagement geometry is necessary to develop the thermal history of the target and background databases it will appear against. Sensor specific criteria such as waveband, field of view, instantaneous field of view, pixel numbers, etc. are needed to process the databases for the candidate sensor. A number of community-standard models are used in KHILS such as the Synthetic Scene Generation Model (SSGM) that implement detailed mathematical descriptions of important signature phenomena. The primary code used to generate target radiometric databases in KHILS is CHAMP[3] (Composite Hardbody and Missile Plume).

CHAMP was developed by KHILS in the late 1980's as a tool to render complex targets, such as missiles with fins, multi-warhead post-boost vehicles, and waking reentry vehicles. CHAMP incorporates the time-dependent signature phenomena, based on computed hardbody thermal response due to radiation and convection heat loads. It also models external source effects, including solar reflection, earth shine, and plume impingement. The CHAMP code has recently been adapted to allow modeling of tactical air breathing targets such as aircraft and cruise missiles[4]. Figure 5 shows examples of CHAMP output for both ballistic missile and air breathing threats. The latest version of CHAMP, CHAMP98, has been completely rewritten in C++ and incorporates many new features that enhance performance, functionality, usability and maintainability. A special real-time version of CHAMP, called FIRE[5] (Fast Image Rendering

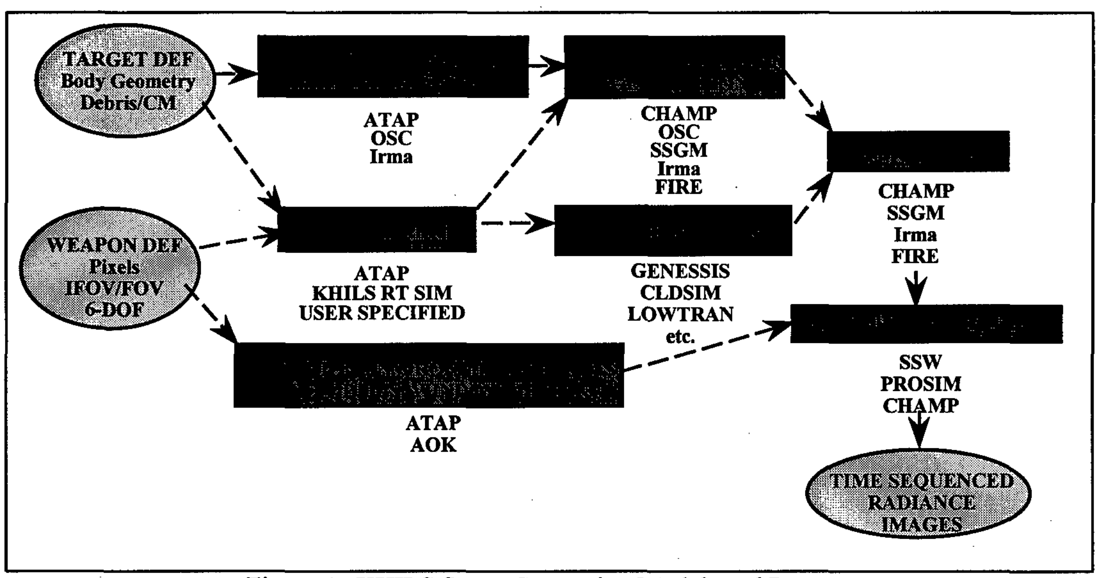

Figure 4. KHILS Scene Generation Models and Process

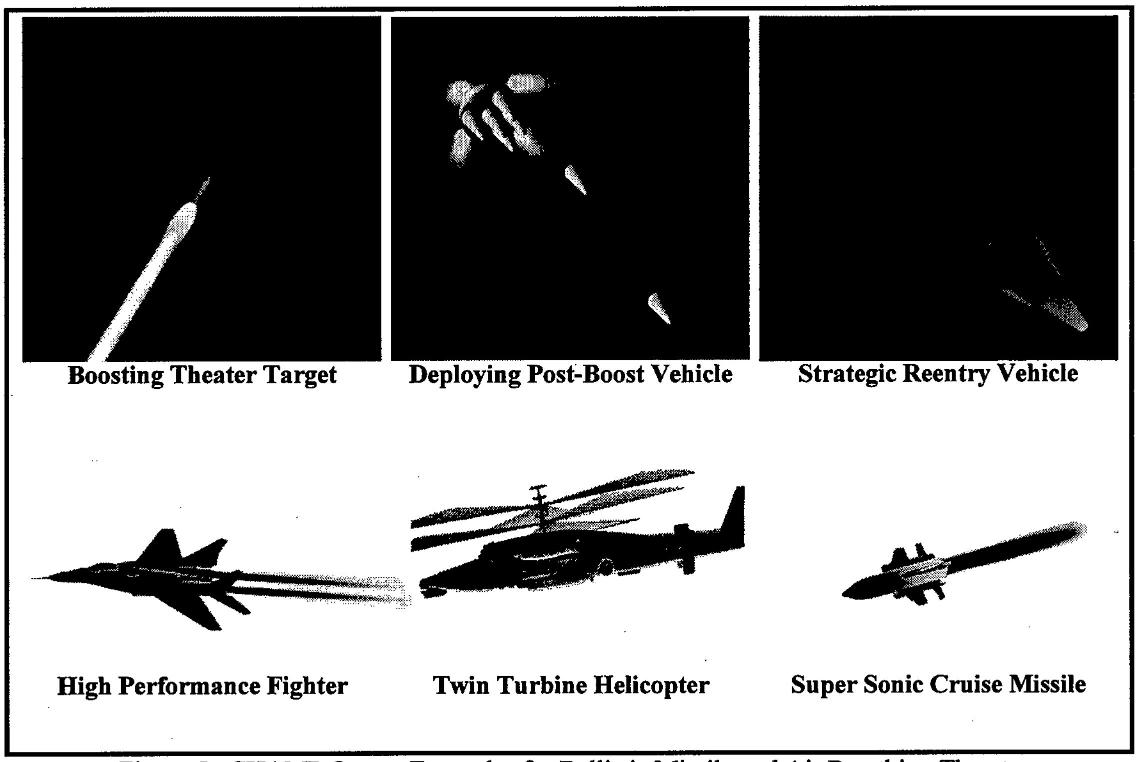

Figure 5. CHAMP Output Examples for Ballistic Missile and Air Breathing Threats

Environment) provides real-time 3-dimensional rendering of composite targets and backgrounds by combining the thermal target modeling capability of CHAMP98 with the rendering capability of high-speed commercial graphics hardware.

CHAMP incorporates temporal profile data from a variety of sources. User specified inputs from flight test thermocouple data may be input directly. Alternatively, CHAMP may use its online radiation, convection, and conduction modules to compute time-dependent surface temperatures. CHAMP may also be augmented with aero-thermal data output of a KHILS developed tool called the Aerothermal Target Analysis Program[6] (ATAP). ATAP models asymmetrical aerodynamic induced heating of complex cruciform missile configurations for transonic to hypersonic speeds within the continuum and rarefied gas regimes.

In addition to providing imagery for KHILS, CHAMP has been used extensively to provide large quantities of image data to outside customers in support of algorithm development. CHAMP has also been integrated into a nonreal-time closed-loop testbed environment that supports module plug-ins of high fidelity seeker models, signal and guidance processing, and full six-degree-of-freedom trajectory dynamics. This capability has been used in support of the THAAD and Unmanned Air Vehicle/Boost Phase Interceptor (UAV/BPI) programs.

B. Real-Time Scene Generation

Real-time IR scene generation refers to the process by which the databases described in the above section are formatted and presented to either a projection or signal injection system. Historically, the preferred and proven method of real-time scene generation has been to window a seeker's field-of-view from a sequence of oversized pre-generated 2-D images based on range and line-of-sight orientation. This method fixes the target aspect angle. For hit-to-kill intercept conditions, this does not significantly impact fidelity since the engagement kinematics do not allow the intercept to vary much beyond a predicted path. In this mode, the most complex phenomenology codes can be used to describe the signature with little regard for execution time. The drawback to this technique is that the scene modeling process requires significant turn-around

time to generate a new movie or scene sequence. Rendering a new set of image sequences using the CHAMP software requires about an hour provided the databases exist. More recently, commercial off-the-shelf graphics computers have demonstrated the ability to render complex 3-D images at seeker frame rates. However, tradeoffs must be made between image fidelity and rendering speed. If not understood, overall image intensity can be in error by many times the correct value based upon the rendering techniques used by the graphics computer. The following sections describe both the 2-D and 3-D rendering in more detail.

1) 2-D Scene Rendering. Rendering of imagery for dynamic presentation to either a scene projector or signal injection interface has been accomplished at KHILS since 1988. Commercial high speed bulk memory boards, special purpose rendering hardware, and custom interfaces are contained in the system shown in Figure 6 called the Scene Generator Random Access Memory (SGRAM). Single oversized frames of imagery, representing a particular range to the target, are rendered to subpixel accuracy based on line-of-sight (LOS) information provided by the real-time simulation computer. The LOS data represents the azimuth, elevation, and roll orientation between the sensor and target. Oversizing the input image allows the sensor FOV to be "windowed" from the larger frame without passing over image boundaries. Strict attention is paid to latency performance through a pipelined architecture and First-In-First-Out (FIFO) input/output devices. Since its initial development, SGRAM has gone through several upgrades. Today, the SGRAM-II is an integral part of the KHILS projector suite supporting 32 Mpixels/sec operation updating a 512 x 512 projection device at over 120 Hz.

2) 3-D Scene Rendering. Real-time all-aspect rendering of targets using commercial off-the-shelf graphics computers has recently been demonstrated in several HWIL facilities[7,8]. This capability has been made possible through commercial developments to support visual training simulators. Attempts by both the Army and Air Force in the middle to late 1980's to develop 3-D renderers resulted in extremely expensive one-of-a-kind systems that were difficult to maintain and lacked upgrade paths. The introduction of the Silicon Graphics Incorporated (SGI) Oynx/Reality Engine made basic 3-D rendering available at a moderate price (<$300K). SGI has recently introduced the Oynx-II/Infinite Reality that represents current state-of-the-art. The 3-D systems compromise accuracy in rendering targets, particularly small or point source objects. This limitation is inherent to the rendering techniques needed to achieve real-time frame rates and, while adequate for human interaction, results in large intensity errors making it potentially unsuitable for HWIL applications. This problem is depicted in Figure

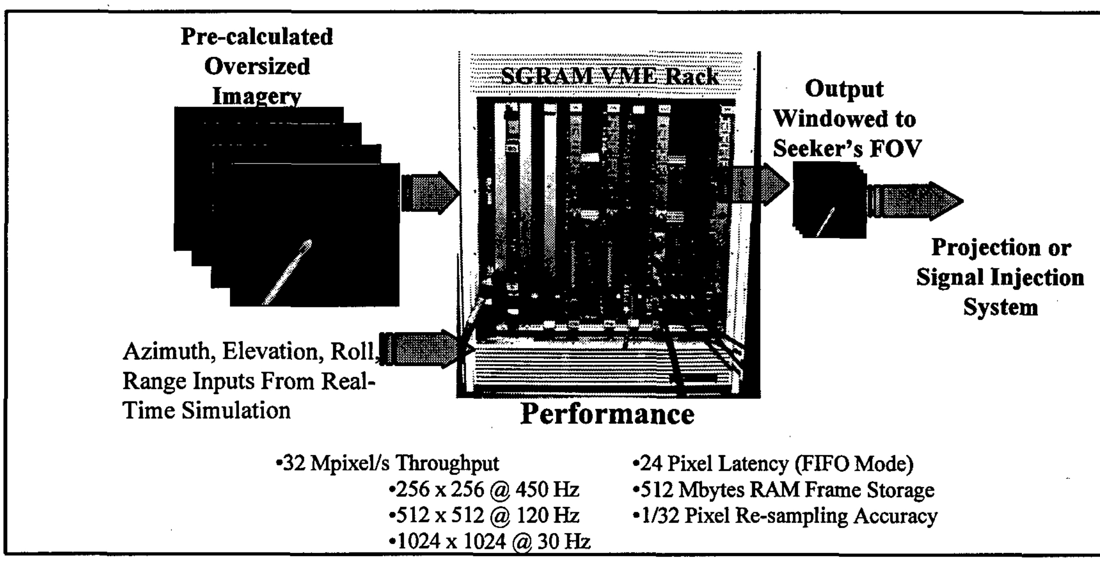

Figure 6. 2-D Playback System: SGRAM

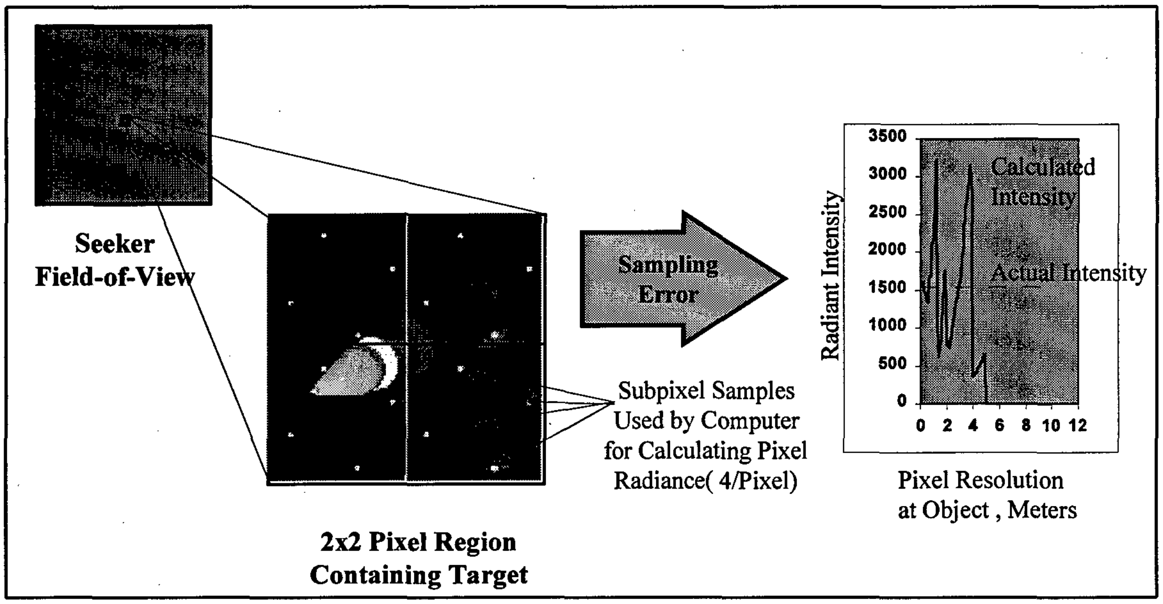

Figure 7. Example of Sampling Errors When Rendering Small Objects

7, where the rendering process uses 4 "line-of-sight" samples per pixel (denoted by the dots within each pixel boundary) to determine the radiance value of that pixel. The target has a small but significantly bright region within a pixel that is ignored because it is not seen by the "line-of-sight" samples made by the computer. The plot in Figure 7 shows this result in the widely varying fluctuations in the calculated intensity output. KHILS staff identified these shortcomings[9] and developed[10] and implemented[8] novel anti-aliasing techniques to minimize these rendering errors. The Zoom Window[10] approach maintains a dynamic high-resolution window around the target and forces the computer to super-sample the target to maintain a given level of accuracy. Naturally, as the number of objects is increased, rendering performance is curtailed. Rendering errors of less than 1% are achievable with four 2000 polygon targets rendered at a 120 Hz frame rate. This requires oversampling each pixel 64 times. Additional CPUs for pixel operations, and Raster Managers, for polygon processing, can be added to meet more demanding requirements.

C. <u>Infrared Scene Projection.</u>

The requirement to perform HWIL testing on imaging sensors having autonomous discrimination, track, and aimpoint algorithms mandates a robust projection capability. Early infrared projection was limited to simplified setups involving blackbodies, cut outs, and motorized irises. More complex representations using halftone image films that were back illuminated by a blackbody source and integrated into zoom optical systems were later fielded. These sufficed for non-imaging and pseudo-imaging sensors having relatively simple signal processing but were woefully inadequate for the emerging class of imaging sensors having focal plane arrays that utilized sophisticated image processing algorithms. During the middle to late 1980's, KHILS sponsored various research and development efforts to advance dynamic infrared projection technology. Technologies based on Liquid Crystal Light Valves (LCLV), Scophony scanned lasers, IR emitting phosphors, and resistive element arrays have undergone extensive characterization within the facility. Currently, the primary projection technology used in KHILS is the resistive element array that is associated with the Wideband Infrared Scene Projector (WISP) program. The WISP has been augmented with another projection device known as the Steerable Laser Projector (SLP) which uses lasers to simulate dynamic high-intensity point sources. When used alone or in combination, both the WISP and SLP give KHILS the unique capability to test imaging IR Sensors and their algorithms in an integrated HWIL environment. A follow-on to the WISP program is underway called the Multi-Spectral Scene Projector (MSSP). The MSSP program will iterate on the

basic design of the WISP resistor array while addressing radio frequency (RF) hardening for operation in an anechoic chamber. Another projection capability exists for supporting Laser Radar (LADAR) HWIL, called the Optical Signal Injector (OSI). The WISP, MSSP, SLP, and OSI systems are discussed further in the following sections.

1) Resistor Array Development. Resistor array technology capitalizes on the advances in the silicon micro-machining industry over the past 15 years. Development sponsored by the Air Force Armament Laboratory (AFATL) in 1985, led to the demonstration of the first large-scale (128 x 128 pixels) resistor array built by Electo-Optek Corporation. This device, called the Resistor Array Projector Prototype (RAPP) was successfully integrated into KHILS where closed-loop operations were conducted in 1992. The RAPP system served to demonstrate the feasibility of extending this technology to larger pixel numbers, higher temperatures, and increased yields. Mission Research Corporation (MRC), having monitored the RAPP program, recognized the potential of achieving better performance with resistor arrays based on uncooled micro-bolometer technology. Considering the Helmholtz Reciprocity Theorem, where a good receiving antenna can also be made to be a good transmitting antenna, MRC proposed to Honeywell that the Honeywell bolometer arrays be run in reverse. The emitter operates on the simple electrical principle that, for constant resistance, the heat generated is directly related to the applied voltage. The Honeywell[11,12] technology, shown in Figure 8, places the resistor or thermal bridge at a precise distance above a reflective substrate creating an optical cavity from which the resulting optical interference is used to tune the spectral emission. Each emitter is individually addressed with a dedicated sample and hold circuit enabling the emitter to continue radiating at a constant level until it is addressed again. The vertical arrangement of the emitter to the underlying substrate containing the multiplex and drive circuitry allows precise tuning of the emitter size for radiometric and temporal performance. Honeywell began development and fabrication of 128 x 128 arrays demonstrating near perfect yield on the Nuclear Optical Dynamic Display System (NODDS) program for the Defense Special Weapons Agency (DSWA, formerly Defense Nuclear Agency (DNA)). Later, 512 x 512 devices were built for Arnold Engineering Development Center (AEDC) as a part of the Cryovacuum Resistor array Infrared Scene Projector (CRISP) program. The KHILS sponsored Wideband Infrared Scene Projector (WISP) program sought to leverage off the NODDS and CRISP programs to build a high temperature, high speed, high yield 512 x 512 resistor array scene projection device that operated at room temperature. The WISP program and its follow-on the Multi-Spectral Scene Projector (MSSP) are discussed below in more detail.

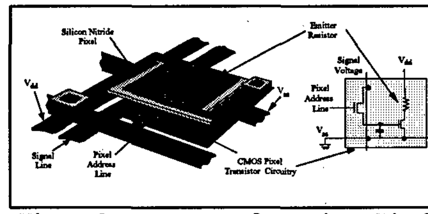

Figure 8. Anatomy of a Resistor Pixel

2) Wideband Infrared Scene Projector (WISP). The goal of the WISP program was to design, fabricate, and integrate into the KHILS facility a 2-color high-temperature 100 Hz 512 x 512 resistor array projector system. Awarded in 1993 to a Contraves-Honeywell team, the WISP is in the final phases of development and has met or exceeded the performance goals set out for the program (Table 2). Although dynamic range appears to be short of the specification, the measured value was driven by two factors: 1) maximum drive voltage and 2) the levels to which higher performing emitters must be limited

Parameter	Specification	Actual (Measured*)
Array Size, Pixels	512 x 512	512 x 512
Pixel Pitch, mil	2 x 2	2 x 2
Dynamic Range (after NUC, w/ 280K Reference)		
1.5-5 μm	1000:1	639:1**
5-12 μm	10:1	7.5:1**
Frame Rate, Hz	100	120
Dead Row/Columns	0/0	0/0***
Flicker	1%	<1%
Corrected Nonuniformity	1%	<1%

* Performance Obtained from Pre-Production (Phase II) Arrays
**Subject to increase with higher drive voltages
***Demonstrated on 1 array

Table 2. WISP Specifications & Performance

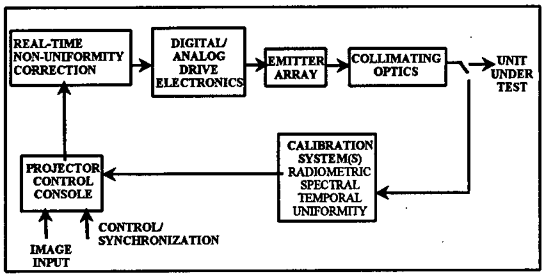

Figure 9. WISP Components

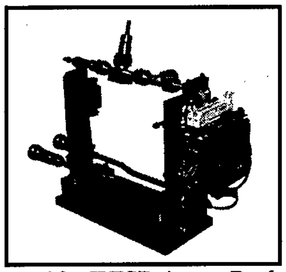
Figure 10. WISP Array Package

to accomplish non-uniformity correction. Table 2 reflects a mid-range drive voltage level that is well within the "safe" operating range of the WISP arrays. Dynamic ranges in excess of 1000:1 have been measured at higher drive voltages. In addition, the non-uniformity levels were such that, to obtain acceptable yield, the higher performing emitters were limited by the maximum output of the lowest acceptable emitters. The final arrays will seek to improve on this with higher inherent uniformity. To support two-color operation, two resistor arrays have been integrated into a common optical system that allows selectable broadband/narrowband 2-color projection operation. The optical system has a zoom feature that allows continuous adjustment of the field-of-view from 1.5-3.0 degrees. Much of the support infrastructure, i.e. control console, interface and drive electronics, and calibration system were developed in-house by KHILS staff to contain costs on the program. Shown in Figure 9, the WISP includes a user interface and control environment that takes scene input from a variety of sources. Specifically, the system can run in one of four modes: 1) a stand alone mode using pre-stored imagery or test patterns for static operations, 2) stand alone mode using video tape input for demonstration purposes, 3) closed-loop mode using scenes stored in RAM and played back through the SGRAM-II, or 4) closed-loop mode using scenes input from the SGI scene generation computer. Currently, a total of 3 pre-production arrays (Figure 10) are supporting HWIL operations in KHILS. Two of the KHILS setups are shown in Figure 11. KHILS staff have assisted the Air Force Development Test Center's 46th Test Wing at Eglin AFB, FL by integrating a WISP onto the target gimbal of a 5-axis flight motion simulator (Figure 12) in the Guided Weapons Evaluation Facility (GWEF) in support of air-to-ground missile HWIL operations. The GWEF is tasked with providing operational test and evaluation support to the Air Force and works closely with KHILS developers to leverage BMDO developed HWIL test technologies for tactical Air Force applications.


5:1 Zoom Optical System

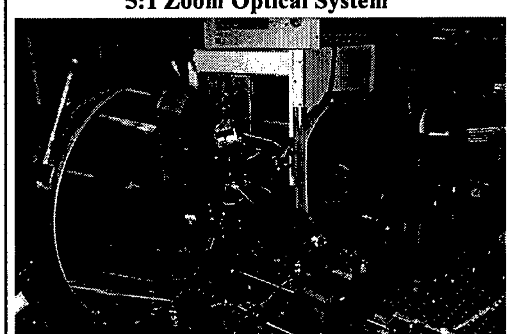
2:1 Zoom Optical System

Figure 11. WISP Integrated in KHILS

A major activity for the pre-production arrays has been the spectral, temporal, and uniformity characterization of each array[13]. The arrays have been confirmed as having broadband spectral performance. Temporal performance exceeds the 10-90% radiance rise-time specification of 100 Hz. WISP arrays are run routinely at speeds as high as 120 Hz. Two-color operation has also been demonstrated where two arrays were co-aligned and calibrated through a common optical train[14]. Still ongoing is the development of the

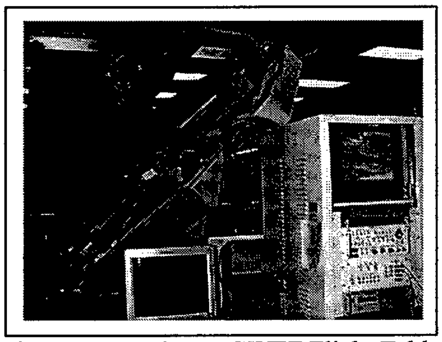

Figure 12. WISP on GWEF Flight Table

non-uniformity characterization techniques of the pre-production arrays. Non-uniformity performance of less than 1% has been achieved on these devices using simplified methods[15]. Further improvements are expected in both non-uniformity levels and calibration time as these techniques are refined in anticipation of the final array deliveries from Honeywell in the summer of 1998. An output example from a WISP array is shown in Figure 13.

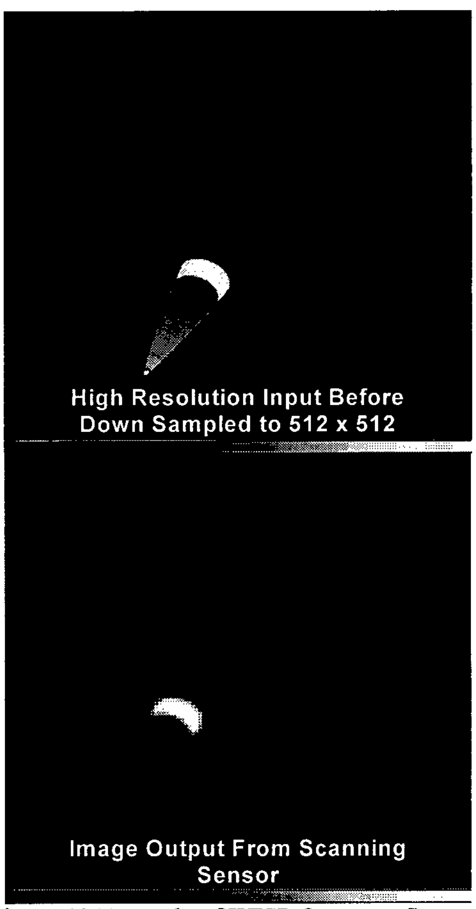

Figure 13 Example of WISP Output as Imaged by an AGEMA 900

3) <u>Multi-Spectral Scene Projector (MSSP).</u> The MSSP program is a follow-on to the WISP program that seeks to develop a radio frequency (RF) hardened projector system for use in RF/IR HWIL testing. The MSSP array will retain all the performance features of the WISP while adding design improvements to the underlying drive circuitry. Specifically, these improvements include the addition of a 3rd level of metalization to the array substrate to reduce electronic crosstalk during array addressing and a snapshot update to minimize synchronization issues with the unit under test. Unlike the majority of KHILS developed technologies, the MSSP is funded principally by the Central Test and Evaluation Investment Program (CTEIP) as a part of a tri-service initiative to establish an IR/RF HWIL capability within each of the services. The service partners include the U.S. Army Aviation and Missile Command (AMCOM) in Huntsville, AL and the Naval Air Warfare Center (NAWC) in China Lake, CA. The first 512 x 512 MSSP arrays will arrive in late FY99.

4) <u>Steerable Laser Projector (SLP).</u> The SLP projector was developed in conjunction with the WISP program as a risk reduction effort to address the challenges of projecting multiple high intensity point source targets. This requirement was driven by the need to test seeker algorithms exercised during the designation/discrimination phase of an interceptor's fly-out. During this phase the target and accompanying objects are unresolved. These algorithms distinguish the target from debris or countermeasures by performing a precise temporal, spatial-position, and radiometric analysis of the environment imaged by the sensor. The SLP supports this test requirement by using 6 mid-wave IR lead-salt laser diodes that are independently steered within the seeker's field-of-view. The output of each laser is independently controlled with a 2000 Hz command update rate. Together, these spatial, radiometric, and temporal controls (Table 3) give the SLP the ability to simulate a wide variety of engagement scenarios including objects that are closely spaced, modulating, extremely hot, dim, etc. Scene generation for the SLP differs from that performed for the WISP in that only a time-history of azimuth, elevation, and intensity control are needed to drive each laser. This data may be either calculated in 3-dimensional space

Parameter	Value
# Sources	6
Waveband, µm	3.8 +/- 0.1
FOV , deg	4.0
Pupil Dia., in	5.5
Optical Resolution, µrad	7.5
Positioning Accuracy, µrad	1.1
Beamsteering BW, Hz	520
Max. Apparent Temp, K	3200
Amplitude Resolution, bit	16
Amplitude Bandwidth, Hz	2000

Table 3. SLP Performance Summary

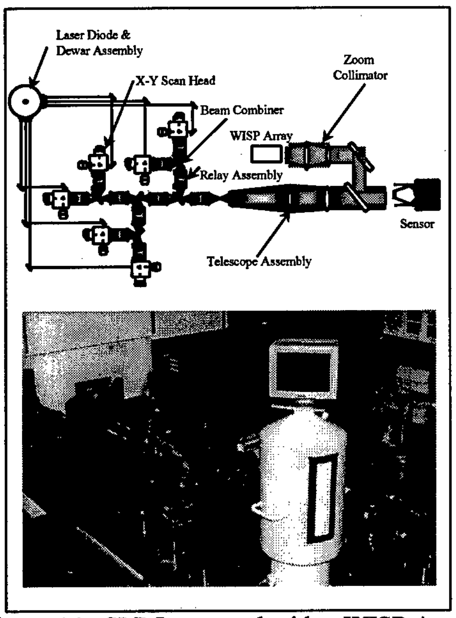

Figure 14. SLP Integrated with a WISP Array

at real-time rates on the KHILS simulation computers or played back from a pre-stored data file.

The SLP has been integrated with a WISP array (Figure 14) to give maximum flexibility for continuous acquisition to endgame testing. In this test setup, the target is projected with the WISP, which is configured to over-sample the center of the sensor's field-of-view while the SLP projects debris objects over the entire field-of-view. Alternatively, the WISP could be used to project the target once it becomes resolved (greater than a few pixels) and the SLP used for projecting all objects during designation/ discrimination. In yet another mode, the WISP/SLP system can be used when hot sources are needed on or in the presence of an extended object such as a hot nose tip of a re-entry vehicle, engine/rocket exhaust nozzles, hot debris being ejected from a booster, or flare countermeasures. Figure 15 shows several examples of output from the WISP/SLP system as seen by a mid-wave IR sensor. The WISP/SLP system has gone through a full radiometric, spatial, and non-uniformity calibration process[16,17] and has been extensively characterized[18] to determine the system's noise/resolution limits.

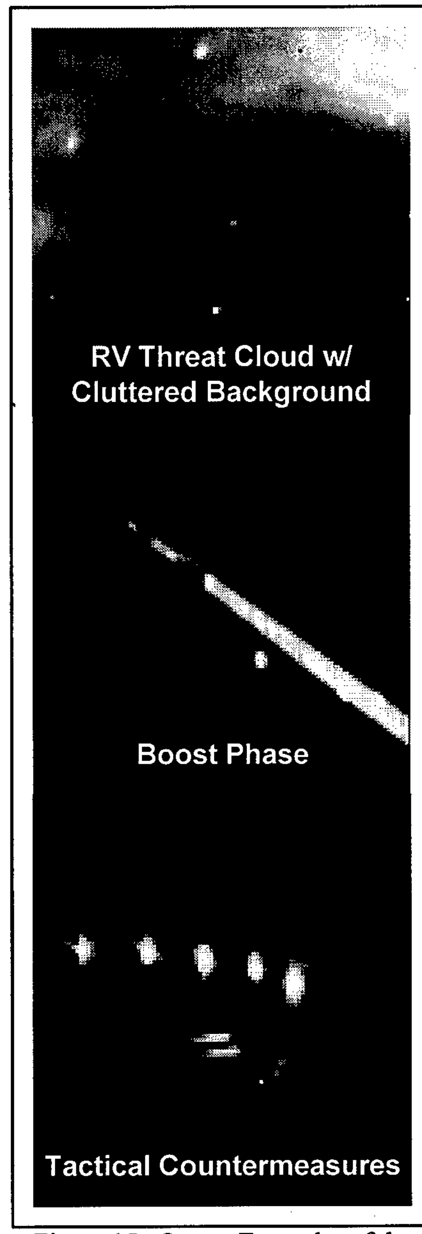

Figure 15. Output Examples of the Combined WISP/SLP Systems from an Amber MWIR 128 x 128 Sensor

D. KHILS Vacuum Cold Chamber (KVACC).

The KVACC[19] provides KHILS the capability to perform HWIL testing on seekers requiring below ambient background environments. This requirement was primarily driven by the sensors associated with the Ground Based Interceptor (GBI) program but also has applicability to the Navy Theater Wide Standard Missile III (NTW SMIII) and THAAD programs. Shown in Figure 16, the KVACC consists of three major chambers

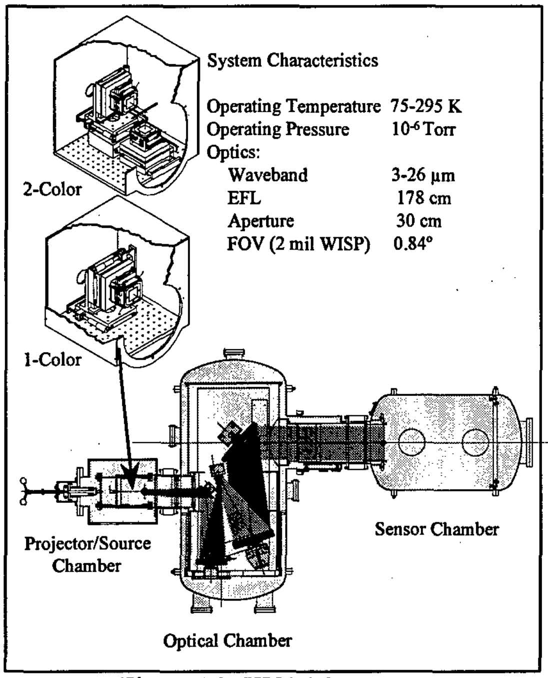

Figure 16. KVACC Layout

separated into main functional areas: source, optics, and sensor. The main chamber houses a five mirror all-reflective broadband optical collimator on an athermal mounting structure along with the primary cold shield. The source antechamber was sized to house two co-aligned resistor arrays for two-color operation. The sensor antechamber contains a 15" x 38" optical bench to mount the unit under test. Gate valves separate the chambers and allow quick turnaround when accessing either the source or sensor antechambers. The system features a closed cycle helium refrigerator and a remotely controlled self-contained Jones Source calibration device.

KVACC development was slowed in recent years due to funding shortfalls but has resumed with the integration of a WISP resistor array planned in late FY98 with a second array to be added in January 1999 for two-color operation. Although the KVACC can be cooled to about 75 Kelvin (K), the WISP arrays are limited to 200 K operation. If lower operating temperatures (down to 75 K) are required, the NODDS resistor array technology developed by the DSWA can be incorporated. This is a straightforward procedure in that the same drive electronics and control environment used for WISP can be used for the NODDS arrays. A significant challenge in demonstrating KVACC operation will be in the calibration and non-uniformity correction of the projection system while at cold temperatures within KVACC. A sensor development effort is underway to provide KHILS this capability while providing an interim surrogate sensor to conduct closed-loop operations.

E. Advanced Development

1) Advanced IR Scene Projector (AISP). Current IR projection technology is limited to 512 x 512 pixel formats with multiplexed updates at 120 Hz. This is adequate for HWIL bench testing (see Mode 2 in Figure 3) of today's 256^2 class of sensor by providing a 2:1 Nyquist sampling. The Nyquist ratio of 2:1 is accepted as the minimum sampling ratio between a projector and sensor. Problems may arise when testing this same sensor on a flight table (Mode 1 in Figure 3) when a 1:1 sampling is used. This limitation, coupled with HWIL test requirements for snapshot focal planes, super-resolution algorithms, and/or larger focal plane array formats, identify a need to develop larger, higher speed projection systems. This requirement is particularly critical for HWIL testing of highly integrated test articles on a flight motion simulator where the inertial instrumentation and electronic image motion compensation algorithms are being exercised. The next logical step for projector performance is a 4X increase in pixel format to 1024 x 1024 pixels and bandwidth to 120 Mpixels/sec (200 Hz), for a total of 8X overall bandwidth increase over the WISP technology. KHILS intends to begin development in late FY98 of such a projection device through an inter-service cooperative arrangement that will pool funds from interested organizations to demonstrate these next generation devices by the 2001-02 time frame.

2) Flight Motion Simulator Development. In 1988 KHILS developed a Carco Flight Motion Simulator optimized for lightweight space based interceptor concepts. Simulator range of travel was limited (+/- 10 deg) in order to achieve unprecedented dynamic response (60 Hz). Since that time the simulator was upgraded with an interchangeable set of hydraulic actuators to allow for approximately a factor of two increase in travel at the expense of bandwidth. This upgrade gave KHILS the flexibility to reconfigure for larger low altitude endo-atmospheric weapons. A five-axis FMS is currently on contract with Carco, geared toward perceived boost phase interceptor requirements. This will also allow for a larger payload mass and volume, true-LOS simulation with target motion represented by a WISP projector on the outer gimbal, and a much-extended range of travel for "over-the-shoulder" engagement scenarios. A design study is also under way to develop a test-bed for image motion compensation schemes on seekers. The goal of the design is to build a device that can accurately duplicate rigid body and vibratory motion at the base of the seeker in excess of 1000 Hz.

3) LADAR Scene Generation Development. Laser Radar (LADAR) seekers have shown promise in providing a low-cost alternative for weapons requiring an imaging capability. For BMDO applications, LADAR is used as an auxiliary sensor to perform discrimination functions. Tactical applications, on the other hand, use LADAR as the primary sensor performing all functions from acquisition to endgame.

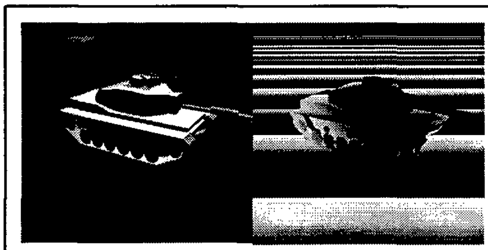

Figure 17. LADAR Image Example

The KHILS facility has developed a unique test and evaluation capability, for a tactical air-to-surface application, using Silicon Graphics Industry (SGI) rendering hardware to perform real-time LADAR scene generation. This system uses observer to target/background pixel range values calculated in an intermediate step of the SGI rendering process[20] to create a "range image" as in Figure 17. The resulting data can be used for digital signal injection or for optical injection. Optical injection is a form of projection where optical pulses, representing the relative returns from a single laser pulse, are generated and fed directly via fiber optics into the receive channels of the sensor. This capability is referred to as the Optical Signal Injector (OSI)[21] and was designed by Aegis Research of Huntsville, AL to provide eight simultaneous channels of laser energy to stimulate the pulse capture system of the Low Cost Autonomous Attack System (LOCAAS). Timing accuracy of better than half a nanosecond has been demonstrated. Limitations in producing arbitrary pulse shapes and high-resolution amplitude control of the current generation OSI will be addressed in upcoming years. Enhancements to the LADAR scene generation system are also being investigated to allow for simulation of complex extended backgrounds, material reflectance characteristics, and laser beam spatial extent.

IV. Summary

The KHILS facility has been under development since 1986 to provide the BMDO with an independent government owned, national test resource for the accomplishment of nondestructive performance testing of precision guided missile systems and subsystems. KHILS' IOC in 1988 demonstrated a LCLV driven by videotape for SBI testing. Over the last 10 years, KHILS has continually pushed the state-of-the-art of HWIL technologies. In recent testing KHILS has demonstrated closed-loop operations with high fidelity phenomenology models hosted on a 3-D all-aspect scene generation computer whose output drove a large format resistor array augmented by a laser source projector system. Development and refinement of the resistor array projectors is being addressed with the WISP and MSSP programs. A low background test chamber is being brought on line to support HWIL testing of sensors requiring low temperature background environments. Advanced development has begun on 1024 x 1024 high-speed resistor array projection devices and a 5-axis flight motion simulator.

V. Acknowledgments

KHILS is a team effort. The authors gratefully acknowledge the dedication and enthusiasm of the KHILS engineering and support staff without whom KHILS would not be the national test resource it has become. We would also like to thank Steve Kessinger, Al Korewjo, Eric Hedlund, and Chet DeCesaris whose sponsorship through the SDIO/BMDO over the last ten years has allowed KHILS to make significant breakthroughs in HWIL test technologies.

VI. References

1. DeCesaris, Millner, Forst, "Role of interceptor hardware-in-the-loop testing in ballistic missile defense programs," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing, Proceedings SPIE 2741, pp. 2-13, (1996).

2. "KHILS Facility Description and Test Article Interface Document, June 1998," Guidance Simulation Branch, Advanced Guidance Division, Munitions Directorate, Air Force Research Laboratory, Eglin Air Force Base, Florida.

3. Crow, Coker, "Composite hardbody and missile plume (CHAMP 98) IR target scene generation program," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing III, Proceedings SPIE 3368, (1998).

4. Garbo, Olson, Crow, Coker, Cunard, "Infrared model development for a high-speed imaging fuze," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing III, Proceedings SPIE 3368, (1998).

5. Crow, Coker, Garbo, Olson, "A closed-loop real-time infrared scene generator," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing III, Proceedings SPIE 3368, (1998).

6. Trolier, Hall, Tincher, Leone, "Aerothermal Target Analysis Program – Engineering Document", AFRL/MNGG, June 1998.

7. Buford, King, Bowden, "Low cost real-time infrared scene generation for image projection and signal injection," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing, Proceedings SPIE 3368, (1998).

8. Olson, Coker, Coker, Garbo, "A demonstration of innovative techniques used for real-time closed-loop infrared scene generation," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing III, Proceedings SPIE 3368, (1998).

9. Garbo, Olson, Coker, Crow, "Real-time three-dimensional infrared scene generation utilizing commercially available hardware," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing, Proceedings SPIE 2741, pp. 166-178, (1996).

10. Olson, Garbo, Crow, Coker, "Rendering energy-conservative scenes in real time," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing II, Proceedings SPIE 3084, pp. 250-259, (1997).

11. Cole, Higashi, Ridley, Holmen, Arendt, Malone, Stockbridge, Goldsmith, Jones, "512 x 512 WISP (wideband infrared scene projector) arrays," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing, Proceedings SPIE 2741, pp. 81-93, (1996).

12. Cole, Higashi, Ridley, Holmen, Benser, Stockbridge, Murrer, Jones, Burroughs, "Recent progress in large dynamic resistor arrays," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing II, Proceedings SPIE 3084, pp. 58-70, (1997).

13. Jones, Stockbridge, Andrews, Herald, Guertin, "Characterization measurements of the wideband infrared scene projector resistor array: II," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing II, Proceedings SPIE 3084, pp. 31-47, (1997).

14. Jones, Coker, Garbo, Olson, Murrer, Bergin, Goldsmith, Crow, Guertin, Daugherty, Marler, Timms, "Demonstration of KHILS' two-color infrared (IR) projection capability," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing III, Proceedings SPIE 3368, (1998).

15. Jones, Olson, Murrer, Andrews, "Simplified method for the hardware implementation of

nonuniformity correction on a resistor infrared scene projector," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing II, Proceedings SPIE 3084, pp. 139-150, (1997).

16. Kircher, Thompson, Cornell, "Integration and calibration of the steerable laser projector with the wideband infrared scene projector," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing II, Proceedings SPIE 3084, pp. 151-162, (1997).

17. Kircher, Marlow, Mackin, "Characterization Measurements of the wideband infrared scene projector (WISP) combined with the steerable laser projector (SLP)," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing III, Proceedings SPIE 3368, (1998).

18. Marlow, Flynn, Kircher, "Radiometric, noise, and spatial characterization of the wideband infrared scene projector," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing III, Proceedings SPIE 3368, (1998).

19. Lippert, Timms, "Capability and integration test of the KHILS vacuum cryogenic chamber (KVACC)," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing, Proceedings SPIE 2741, pp. 150-156, (1996).

20. Olson, Coker, "Real-time generation for ladar hardware-in-the-loop testing," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing, Proceedings SPIE 2741, pp. 201-108, (1996).

21. Cornell, Naumann, Bergin, "Optical signal injector systems for HWIL testing of ladar seekers," in Technologies for Synthetic Environments: Hardware-in-the-Loop Testing II, Proceedings SPIE 3084, pp. 58-70, (1997).